5. Disappearing filament optical pyrometer calibrations

5.1 Optical pyrometer preparation

Disappearing filament optical pyrometers (DFP) are calibrated from 800 °C to 4200 °C by comparison to the VTBB. When the test unit arrives, the batteries are checked, the objective lens and eyepiece are cleaned, and the eyepiece is focused onto the DFP lamp filament. The lamp is checked to ensure that it is operating and that matching is possible. If an operating manual is not on file, then one is requested from the customer because test pyrometers are operated according to the manufacturer's instructions unless other instructions are given. The pyrometers and associated electronics are initialized according to manufacturer's specifications.

5.2 Optical pyrometer calibration

The DFP is aligned onto the geometric center of the VTBB opening. The DFP is measured at an appropriate distance from the front surface of the objective lens holder to the blackbody cavity partition and is focussed on the center of the partition. After the VTBB is turned on, the pyrometer centering is checked and adjusted as necessary.

For the 800 °C to 2700 °C temperature range, the PEP is used to spectrally compare the VTBB to the WS to determine the radiance temperature of the blackbody at each calibration temperature. The VTBB and the WS are compared three times and the mean is used. Once the temperature of the blackbody has been determined, the test DFP lamp filament is matched in brightness to that of the blackbody, and the DFP lamp current is measured using a standard resistor and a digital voltmeter. The matching is performed from bright to disappearance and from dark to disappearance twice and the mean of the four readings is used. The indicated temperature is recorded for pyrometers with either a temperature scale or a digital panel indicator. The output voltage is measured for pyrometers with internal current measuring resistors. The DFP measurements are not bracketed by VTBB measurements because the VTBB has been shown to be stable to within ± 0.1 °C during the time required to complete the measurements.

For temperatures above 2700 °C, the method used to extrapolate the calibration to 4200 °C involves measuring temperatures below 2700 °C on two or more ranges. For a three-range DFP with a low range (L) from 1100 °C to 1700 °C, a medium range (M) from 1700 °C to 2800 °C, and a high range (H) from 2900 °C to 4200 °C, the following measurements are performed. The DFP lamp currents are measured for VTBB temperatures from 1100 °C to 1700 °C on the L range, from 1600 °C to 2700 °C on the M range, and from 1700 °C to 2700 °C on the H range.

5.3 Optical pyrometer data analysis

The various data reduction methods used are determined by how the DFP indicates temperature. In all cases, the data is sorted by range and averaged and the standard deviation is calculated. For DFPs with ranges below 2700 °C, the data is analyzed and the blackbody temperature versus the scale or panel reading, output current, or output voltage is reported. The pyrometer correction, blackbody temperature minus DFP reading, that is added to the pyrometer reading is reported for scale and panel indicator DFPs.

For the three-range DFP case when temperatures are determined above 2700 °C, more calculations are required before the data is reported. The current measurement averages are fit to the curve $I(T) =$

$a_0 + a_1 \cdot T + a_2 \cdot T^2 + a_3 \cdot T^3$ calculating a least squares approximation for each DFP range. For the L range the blackbody temperatures are calculated at the nominal temperatures 1100 °C, 1200 °C, …, 1700 °C and reported versus the pyrometer lamp currents. For the M range, the blackbody temperatures are calculated at the nominal temperatures 1700 °C, 1800 °C, …, 2700 °C and reported versus the pyrometer lamp currents. The 2800 °C calibration point is determined in two steps. The first step is to calculate A_M, the "A" value [22] for the M range, which is defined be the relationship,

$$A = \frac{1}{T_\mathrm{APP}} - \frac{1}{T_\mathrm{BB}} = \frac{l}{c_2} \cdot \ln t \ , \tag{44}$$

where T_APP is the apparent temperature [K], T_BB is the blackbody temperature [K], t is the filter transmittance, and A is the "A" value [K^{-1}]. From eq (44), it becomes apparent that ln t must be approximately equal to 1/ l in order for A to be constant. Typically, the value of A is on the order of 173×10^{-6} K^{-1}. T_BB, is determined during the M range measurements. T_APP is the temperature on the L range that corresponds to the current measured on the M range which is determined through iteration of the L range function $I(t)$. The second step is to use the "A" value to calculate the pyrometer lamp current that corresponds to the extrapolated blackbody temperature at 2800 EC. Use eq (44) to calculate T_APP2 when T_BB2 = 3073.15 K and $A = A_\mathrm{M}$. Next calculate the pyrometer lamp current using the L range function $I(t)$.

This procedure is repeated to determine the extrapolated blackbody temperatures for the H range. The H range "A-value", A_H, is determined where T_APP is the temperature on the L range that corresponds to the current measured on the H range and T_BB is the blackbody temperature during the H range measurements. A_H is then used to calculate the apparent temperature T_APP2 for each extrapolated blackbody temperature from 2900 EC to 4200 EC. The pyrometer lamp currents are calculated from the L range function $I(t)$. The extrapolated blackbody temperatures for the M and H ranges are reported versus the pyrometer lamp currents.

5.4 Optical pyrometer calibration uncertainty

To calibrate disappearing filament optical pyrometers (DFP), the ratio (r_3) of the spectral radiance of the WS lamp to that of the variable-temperature blackbody (BB),

$$r_3 = \frac{L_l(T_\mathrm{BB})}{L_l(T_\mathrm{WS3})} = \frac{S_\mathrm{BB}}{S_\mathrm{WS3}} \ , \tag{45}$$

is first measured to determine the radiance temperature of the BB, $T(8, L_{8\mathrm{BB}})$, at each disappearing filament optical pyrometer temperature by the equation,

$$T_\mathrm{BB} = \frac{c_2}{n_l \cdot l \cdot \ln\left[1 + \frac{e_{l,\mathrm{BB}} \cdot c_{1L}}{n_l^2 \cdot l^5 \cdot L_\mathrm{WS3} \cdot r_3} \cdot \frac{(C_\mathrm{A} \cdot C_\mathrm{L} \cdot C_\mathrm{S} \cdot G)_\mathrm{WS}}{(C_\mathrm{A} \cdot C_\mathrm{L} \cdot C_\mathrm{S} \cdot G)_\mathrm{BB}}\right]} \ . \tag{46}$$

The uncertainty in the spectral radiance of the BB can be calculated by the RSS of products of partial derivatives of eq (46) with their respective uncertainties as follows,

$$u_0(T_{\mathrm{BB}}) = \left[\left(\frac{\partial T_{\mathrm{BB}}}{\partial n_l} \cdot u(n_l) \right)^2 + \left(\frac{\partial T_{\mathrm{BB}}}{\partial l} \cdot u(l) \right)^2 + \left(\frac{\partial T_{\mathrm{BB}}}{\partial c_2} \cdot u(c_2) \right)^2 + \sum_{i=1}^{12} \left(\frac{\partial T_{\mathrm{BB}}}{\partial x_i} \cdot u(x_i) \right)^2 \right]^{1/2}, \tag{47}$$

where x_{i} is one of the following variables: e_{BB}, c_{1L}, r_3, $C_{\mathrm{A,WS}}$, $C_{\mathrm{L,WS}}$, $C_{\mathrm{S,WS}}$, G_{WS}, $C_{\mathrm{A,BB}}$, $C_{\mathrm{L,BB}}$, $C_{\mathrm{S,BB}}$, or G_{BB}. The partial derivatives of n_l, l, and c_2 can be derived from eq (46) as

$$\frac{\partial T_{\mathrm{BB}}}{\partial n_l} = \frac{T_{\mathrm{BB}}}{n_l} \cdot \left[\frac{e_{l,\mathrm{BB}} \cdot c_{1L}}{n_l^2 \cdot l^5 \cdot L_{\mathrm{WS3}}} \cdot \frac{2 \cdot \dfrac{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{WS}}}{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{BB}}}}{r_3 \cdot \dfrac{c_2}{n_l \cdot l \cdot T_{\mathrm{BB}}} \cdot \exp\left(\dfrac{c_2}{n_l \cdot l \cdot T_{\mathrm{BB}}} \right)} - 1 \right], \tag{48}$$

$$\frac{\partial T_{\mathrm{BB}}}{\partial l} = \frac{T_{\mathrm{BB}}}{l} \cdot \left[\frac{e_{l,\mathrm{BB}} \cdot c_{1L}}{n_l^2 \cdot l^5 \cdot L_{\mathrm{WS3}}} \cdot \frac{5 \cdot \dfrac{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{WS}}}{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{BB}}}}{r_3 \cdot \dfrac{c_2}{n_l \cdot l \cdot T_{\mathrm{BB}}} \cdot \exp\left(\dfrac{c_2}{n_l \cdot l \cdot T_{\mathrm{BB}}} \right)} - 1 \right], \text{ and} \tag{49}$$

$$\frac{\partial T_{\mathrm{BB}}}{\partial c_2} = \frac{T_{\mathrm{BB}}}{c_2}. \tag{50}$$

The expression,

$$\left| \frac{\partial T_{\mathrm{BB}}}{\partial x} \right| = \frac{T_{\mathrm{BB}}}{x} \cdot \frac{e_{l,\mathrm{BB}} \cdot c_{1L}}{n_l^2 \cdot l^5 \cdot L_{\mathrm{WS3}}} \cdot \frac{\dfrac{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{WS}}}{(C_{\mathrm{A}} \cdot C_{\mathrm{L}} \cdot C_{\mathrm{S}} \cdot G)_{\mathrm{BB}}}}{r_3 \cdot \dfrac{c_2}{n_l \cdot l \cdot T_{\mathrm{BB}}} \cdot \exp\left(\dfrac{c_2}{n_l \cdot l \cdot T_{\mathrm{BB}}} \right)}, \tag{51}$$

represents the partial derivatives of T_{BB} with respect to x, where x is one of the variables, e_{BB}, c_{1L}, r_3, $C_{A,WS}$, $C_{L,WS}$, $C_{S,WS}$, G_{WS}, $C_{A,BB}$, $C_{L,BB}$, $C_{S,BB}$, or G_{BB}.

A summary of the DFP variable values in eq (46) in table 11. Uncertainty values from eq (47) are given in table 12. Table 12 also shows the standard uncertainties leading up to the total standard uncertainty in the DFP temperature,

$$\frac{u(T_{\mathrm{BB}})}{T_{\mathrm{BB}}} = \left[\left(\frac{u_0(T_{\mathrm{BB}})}{T_{\mathrm{BB}}}\right)^2 + \left(\frac{u(\mathrm{DMM})}{T_{\mathrm{BB}}}\right)^2\right]^{1/2} . \tag{52}$$

The uncertainty in the pyrometer temperature is related to the uncertainty in the variable-temperature blackbody temperature by the following relationship,

$$\frac{u(T_{\mathrm{DFP}})}{T_{\mathrm{DFP}}} = \left[\frac{u^2(T_{\mathrm{BB}})}{T_{\mathrm{BB}}^2} + \left(\frac{u(\mathrm{BU})}{T_{\mathrm{DFP}}}\right)^2 + \left(\frac{u(\mathrm{PR})}{T_{\mathrm{DFP}}}\right)^2\right]^{1/2} , \tag{53}$$

where u(BU) is the blackbody uniformity uncertainty and u(PR) is the pyrometer reading uncertainty. The relative expanded uncertainty in the DFP temperature from tables 11 and 12 is 7.57 K/2579.07 K, or 0.29 %. The uncertainty values for other DFP temperatures are listed in table 2.

Table 11. Typical values of DFP variables and parameters

Variable	Symbol	Value
Refractive index	n_l	1.00028
Wavelength	l	655.3 nm
Second radiation constant	c_2	14387.69 µm·K
Emissivity of BB	e_{BB}	0.99
First radiation constant	c_{1L}	1.191×10^8 W·µm^4·m^{-2}
WS spectral radiance	L_{WS}	569.9 W·m^{-2}·µm^{-1}·sr^{-1}
Ratio of BB signal to WS signal	r_3	3.445
WS amplifier calibration correction	$C_{A,WS}$	0.09986
WS linearity correction	$C_{L,WS}$	1
WS size of source correction	$C_{S,WS}$	1
WS amplifier gain	G_{WS}	1×10^9 V·A^{-1}
BB amplifier calibration correction	$C_{A,BB}$	9.978
BB linearity correction	$C_{L,BB}$	0.9997
BB size of source correction	$C_{S,BB}$	0.9987
BB amplifier gain	G_{BB}	1×10^7 V·A^{-1}
BB temperature	T_{BB}	2579.07 K

Table 12. Uncertainty budget for the DFP pyrometer temperature calibration

Uncertainty factor	Symbol	Expanded Uncertainty (k = 2) Type A	Expanded Uncertainty (k = 2) Type B
Refractive index	$u(n_\lambda)$		0.00002
Wavelength	$u(l)$		0.2 nm
Second radiation constant	$u(c_2)$		0.24 µm·K
Emissivity of BB	$u(e_{BB})$		0.0002
First radiation constant	$u(c_{1L})$		440 W·µm^4·m^{-2}
WS spectral radiance	$u(L_{WS})$		2.998 W·m^{-2}·µm^{-1}·sr^{-1}
Ratio of BB signal to WS signal	$u(r_3)$	0.00682	
WS amplifier calibration correction	$u(C_{A,WS})$	0.00001	
WS linearity correction	$u(C_{L,WS})$	0.001	
WS size of source correction	$u(C_{S,WS})$	0.0002	
WS amplifier gain	$u(G_{WS})$		0 V·A^{-1}
BB amplifier calibration correction	$u(C_{A,BB})$	0.001	
BB linearity correction	$u(C_{L,BB})$	0.001	
BB size of source correction	$u(C_{S,BB})$	0.0002	
BB amplifier gain	$u(G_{BB})$		0 V·A^{-1}
Digital voltmeter	u(DMM)	0 K	
BB temperature	$u(T_{BB})$		2.34 K
Blackbody uniformity	u(BU)	0.20 K	
DFP reading	u(PR)	7.20 K	
DFP temperature calibration	$u(\mathrm{T_{DFP}})$	**7.57 K**	